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Flow over the Mid Adriatic Pit

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Summary. — The influence of the Mid Adriatic Pit (MAP) on the general circulation of the Adriatic is explored through numerical simulations. The numerical code used is the DieCAST model specifically modified for application to the Adriatic Sea. A ten-year simulation is performed and the ability of the model to capture important features of the Adriatic circulation is demonstrated. A series of numerical experiments on the importance of the MAP on the general circulation is performed. It is demonstrated that the current over the northern flank of the MAP, which flows from the Croatian toward the Italian coast, is primarily a topographic current and that such a current would reverse direction if the gradient of the bathymetry were reversed.

PACS `92.10.Fj` – Upper ocean and mixed layer processes.
PACS `92.10.Iv` – Ocean influence of Earth's rotation.

1. – Introduction

The circulation of the Adriatic Sea is strongly affected by various influences such as bottom bathymetry, surface winds, inflow from the Mediterranean through the Otranto strait, etc. The influence of the topographic structure known as the South Adriatic Pit (SAP) in giving a cyclonic circulation to the South Adriatic is well known and has been well studied. Another significant topographic feature is the Mid Adriatic Pit (MAP, also known as the Jabuka or Pomo Pit). The influence of this feature is less robust than that of the South Adriatic Pit, but nevertheless causes a steering effect that is important in determining the general circulation. Satellite and drifter observations show a cold filament arising near the Croatian coast and moving southwest toward the Italian coast [1]. This filament, known as the Mid Adriatic Filament (MAF), is located above the nothern flank of the MAP. Our object here is to focus attention on the role of the MAP in the general circulation of the Adriatic and to discuss how its topography helps establish the currents that flow over it.

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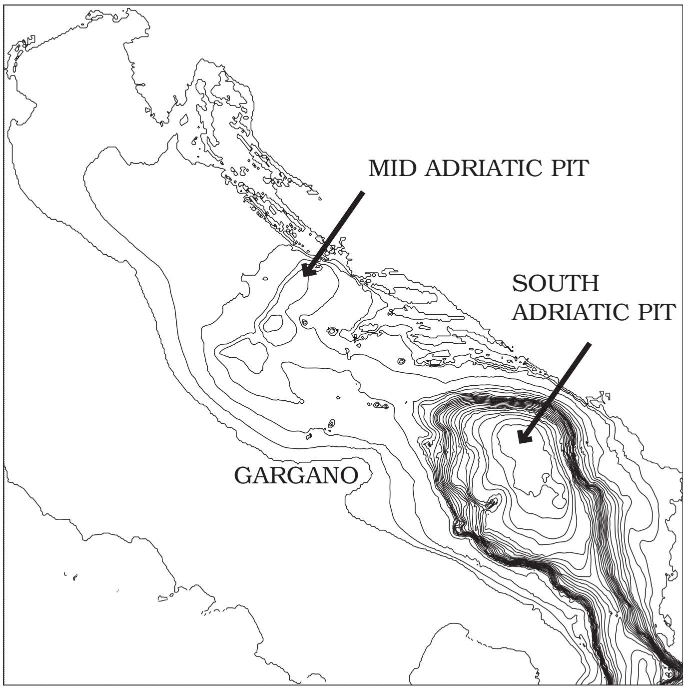

Fig. 1. – Contour plot of the bathymetry of the Adriatic Sea with horizontal resolution of 1 min. The Mid Adriatic Pit is the relatively deep region which nearly transects the Adriatic. The contour interval is 50 m.

The bathymetry of the Adriatic contoured from a data base of 1 min horizontal resolution is shown in fig. 1. The depth contours are drawn at 50 m intervals. The northern end of the Adriatic is much shallower than the southern end. Features of particular note are the South Adriatic Pit, reaching depths of over 1300 m, the Mid Adriatic Pit, reaching depths of over 250 m, and the Gargano promontory.

For various theoretical reasons [2, 3] there should be a strong tendency for the flow in a deep basin to be cyclonic (*e.g.*, counter-clockwise in the northern hemisphere), and, indeed, the flow in the South Adriatic Pit is rather persistently cyclonic. Basically the argument is that fluid constrained to move in a thin layer and subject to strong rotation should behave in a nearly two-dimensional fashion. Fluid parcels can then be considered columns of fluid aligned along the vertical direction. Such columns moving from shallow to deep regions would be stretched while those moving from deep to shallow would be compressed. The conservation of angular momentum with realistically weak dissipation (largest in shallow regions) thus results in creation of cyclonic/anticyclonic relative vorticity. The result is net cyclonic flow in the basin. This is consistent with northern hemisphere mid-size basins, which usually have offshore cyclonic mean circulation and coastal anticyclonic features enhanced by interactions with coastal abutments (*e.g.*, the Black Sea [4]).

The effect of the Mid Adriatic Pit is a bit more subtle. Note that this pit has a rather steep gradient on its northwestern side. We refer to this simply as the northern flank. The topographic gradient on the southeastern side, the southern flank, is relatively mild.

Thus the effect of the northern flank on the current system may be similar to that of a step or an escarpment. The flow in the vicinity of the MAP fluctuates considerably, but is often along the northern flank moving from the Croatian toward the Italian coast (southwestward). This current is often indicated by drifter data [5] and seen in satellite images [1]. Arguments based on double Kelvin wave propagation and Rossby adjustment due to the interaction of a coastal current and the topography can be used to explain its existence [6, 7]. The direction of the current can also be obtained from an argument similar to that given for the basin circulation: motions across the step would tend to produce cyclonic circulation on the deep side and anticyclonic motion on the shallow side. The net result would be motion along the step in the direction facing forward with the shallow fluid on the right and the deep on the left. A simple barotropic quasi-geostrophic theory based on flow of a coastal current over an escarpment takes account of the presence of the East Adriatic Current and predicts a bifurcation and an outflow along the escarpment contours [8]. This theoretical model has recently been verified by laboratory experiments in a rotating tank [9, 10].

Except in the vicinity of the step, the tendency to produce anticyclonic flow north of the step is dominated by the tendency to produce cyclonic flow in the northern shallow region by coastal region mixing. The flow is further complicated by the locally strong influence of the Po River plume. Nevertheless, the currents in the central and northern Adriatic Sea are modified significantly by the presence of the MAP even though it is much shallower than the dominant Southern Adriatic Pit.

Our goal here is to present a few simple numerical simulations that demonstrate the topographic nature of the southwestward MAP current in the framework of a full general circulation model. A history of some early simulations of the general circulation of the Adriatic is given in [11]. Some of the current maps there show a distinct current flowing southwest along the direction of the contours of the northern rim of the MAP. More recently, high-resolution simulations using the DieCAST model (discussed in sects. **2** and **3**) have been presented but without focusing on the effect of the MAP [12]. Here, our approach will be to study and emphasize the effect of the MAP by demonstrating what the Adriatic currents would look like in the absence of this topographic feature and what the effect would be of reversing the sign of its topographic gradient. To do this we will first need to spin-up a reliable general circulation. This will take simulating several years of flow with appropriate wind forcing and surface conditions, as discussed in sect. **4**. Then in sect. **5**, the topography is changed and the effect is noted on the subsequent evolution. In particular, it is demonstrated that changing the sign of the topographic gradient on the northern flank of the MAP results in a reversal of the current flowing over that feature, as predicted theoretically [8]. This paper is an updated and modified version of an earlier conference proceedings article [13].

2. – DieCAST model background

The DieCAST ocean model [14, 15, 4, 16] is used to study the circulation of the Adriatic Sea. The hydrostatic, Boussinesq primitive continuum equations are recovered as an infinitesimal control volume limit of the discrete conservation equations solved by DieCAST. A free-slip quasi-rigid-lid approximation is used. (The "lid" is weakly porous due to evaporation, precipitation and river source treatments [4]). However, efficient free surface and non-hydrostatic options are available; the former uses a shallow-water equations submodel forced by vertically averaged baroclinic mode terms; the latter uses an efficient iteration on the non-hydrostatic vertical acceleration terms [17, 18].

The DieCAST lineage began with the Sandia Ocean Modeling System [17], which included a two-way-coupled three-dimensional bottom boundary layer (bbl) submodel designed for risk assessment under the DOE sponsored Subseabed Waste Disposal Program. By confining sloping coordinates to the thin bbl, such approach avoids inaccuracies and associated numerical problems [19] of baroclinic pressure gradient evaluation in a sloping bottom-fit (*e.g.*, "sigma") coordinate system outside the bbl, while allowing accurate specialized (*e.g.*, having sophisticated subgrid-scale turbulence submodel for Reynolds stress parameterization) treatment of the bbl in a full ocean modeling system.

Resolution sensitivity studies [20-23] verify model numerics and show that higher-order treatment of numerically dispersive interpolations, used to evaluate the large Coriolis terms on the original staggered Arakawa "c" grid, greatly improves accuracy. Although included in these resolution sensitivity studies, the present DieCAST semi-collocated grid approach avoids such numerical dispersion of the large Coriolis terms. The original semi-collocated approach was improved [14] by:

a) RDA (reduced dispersion advection)
b) MIA (modified incompressibility algorithm).

MIA reduces numerical dispersion associated with two-way interpolations used by the incompressibility step. The original RDA is, effectively, 3.5-order-accurate. Following [24, 25], a slightly modified RDA is used in recent versions which is formally fourth-order-accurate on a collocated control volume grid. Third-order-upwind advection is a reasonable alternative, but there are advantages to our present fourth-order-accurate approach.

The present DieCAST model is fourth-order-accurate, except for subgrid-scale diffusive parameterization and vertical integration of the vertical momentum (hydrostatic) equation and in zones adjacent to lateral boundaries, where second-order accuracy is used.

Dietrich and Mehra [26] introduced a robust one-way nesting approach, which has been upgraded in a two-way-coupled nearly seamless duo grid North Atlantic/Gulf of Mexico/Caribbean Sea model that is one-way-nested in a global version of DieCAST [27]; for more details on the basic grid coupling and nesting approach, see: `http://www.maths.unsw.edu.au/ bxs/DieCAST/MANUAL/`.

Results include: highly inertial realistic Gulf Stream separation and dynamics; difficult-to-model warm core rings (pinched off northern meanders of the GS); cold core rings; and a robust Deep Western Boundary Current, not resolved by the initialization climatology, that develops over a time scale $O(10)$ years and significantly affects the GS separation and underlying fields.

Accuracy—including low numerical dispersion—and robustness with low numerical dissipation are extremely desirable features in numerical models. These features, and algorithmic simplicity and numerical efficiency, are serious goals in the DieCAST lineage. However, it is noteworthy that other versions exist that include advanced features such as partial bottom cells and more sophisticated advection and turbulence closure algorithms (*e.g.*, the Canadian version of DieCAST, CANDIE [28]).

3. – Adriatic Sea implementation of DieCAST

The present 30-layer, 2.5 min longitudinal resolution DieCAST adaptation is one-way-nested inside a 7.5 min resolution full Mediterranean Sea adaptation (open southern boundary conditions are derived from the latter). Latitudinal resolution is such that horizontal cell aspect ratio is 1.0 ($dy = dx$). Unfiltered etop05 bathymetry (a NOAA

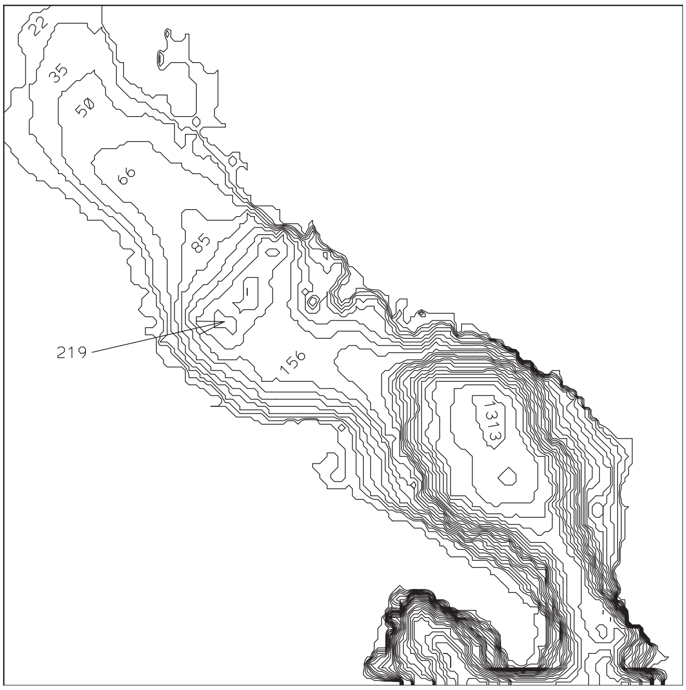

Fig. 2. – Contour plot of the model bathymetry used in our 2.5 min horizontal resolution implementation of the DieCAST model. The bathymetry is represented as 30 discrete steps in the model. Here we label the depth of some of these steps in meters.

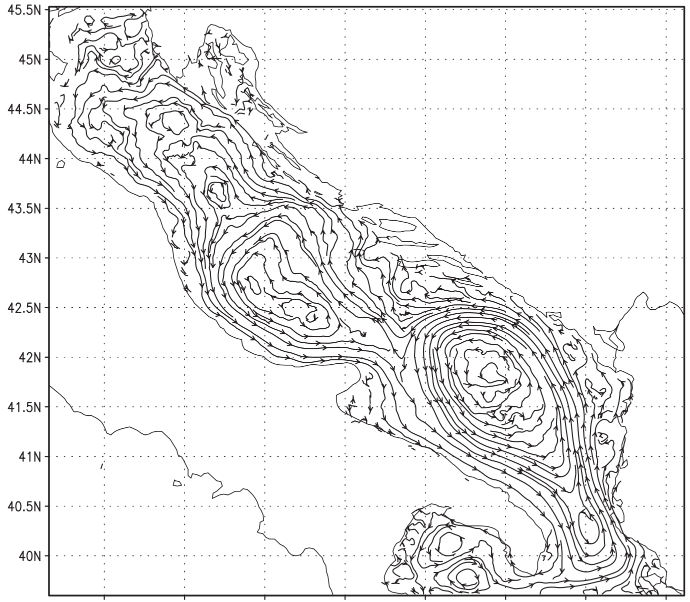

Fig. 3. – Streak plot for the velocity averaged over the fourth year of the simulation.

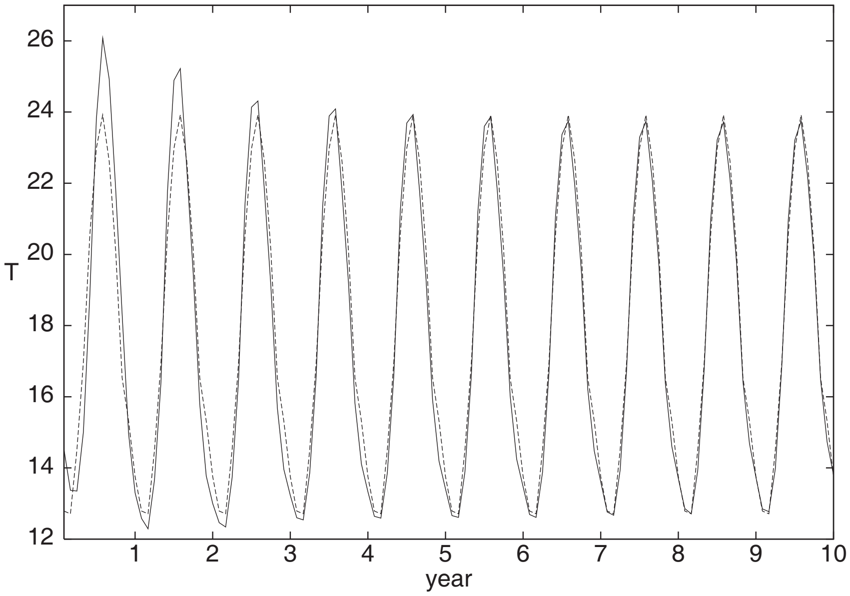

Fig. 4. – Graph of the ten-year history of the horizontally averaged surface temperature from the simulation of the Adriatic. The model data is represented by the solid line while the climatological cycle is the dashed line.

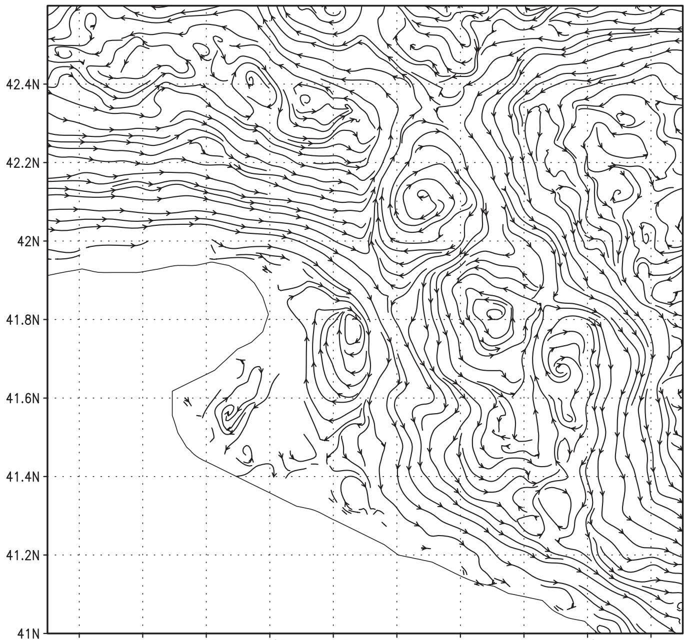

Fig. 5. – Streakline plot showing a recirculation eddy in the lee of the Gargano Peninsula from the end of February in year 10.

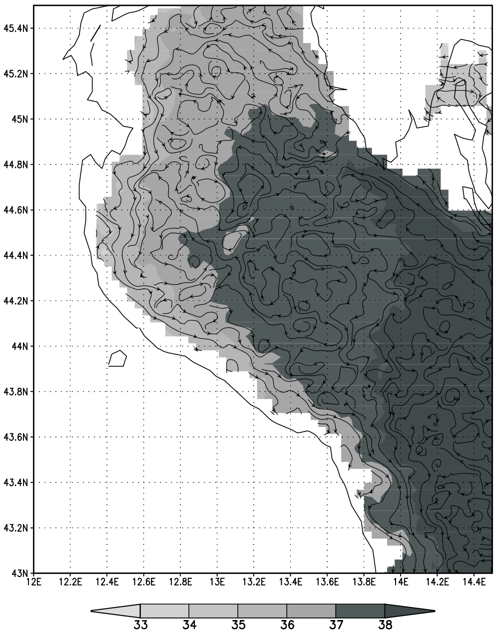

Fig. 6. – Surface salinity at the beginning of January year 10 with superposed streakline plot. This figure indicates the extent of the low salinity Po river plume at the beginning of winter. Values are grams of salt per kilogram of water.

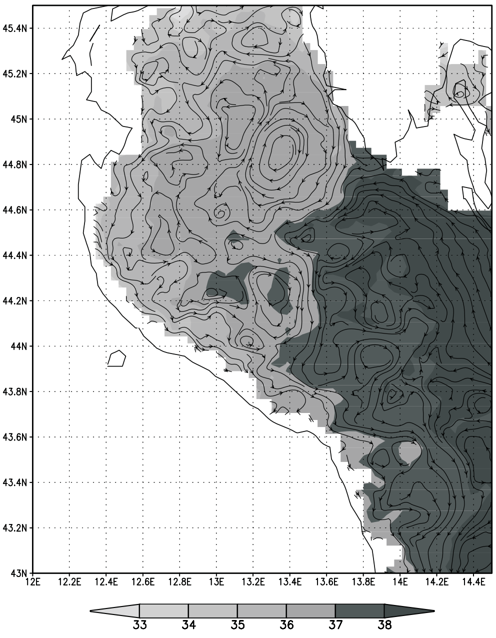

Fig. 7. – Surface salinity at the end of March year 10 with superposed streakline plot. This figure indicates the extent of the low salinity Po river plume in late winter. Values are grams of salt per kilogram of water.

database, see `http://www.ngdc.noaa.gov/mgg/global/etopo5.HTML`) truncated at depth 2750 m is used. Annual cycle Hellerman climatological winds are used (see: `http://ingrid.ldeo.columbia.edu/SOURCES/.HELLERMAN`).

The bathymetry of the Adriatic with 1 min resolution is shown in fig. 1. With the resolution of the current model the bathymetry takes on the form shown in fig. 2.

Thermodynamic surface boundary conditions (heat flux, evaporation, precipitation) are derived from more accurate annual cycle climatological data for surface temperature and salinity, combined with model internal dynamics. In contrast to conventional Haney restoring [29] approaches, this physically motivated new approach that has no phase lag or amplitude damping of the ensemble (multi-year) average annual cycle and does not artificially damp surface fronts. River sources may alternatively be specified directly, as done for 11 rivers in the Black Sea DieCAST adaptation [4] but here are implicitly included in the climatological data when using the new surface boundary conditions approach.

Vertical mixing, described in detail by elsewhere [4], is represented by adding a Pacanowski and Philander [30] surface mixed layer parameterization to background near-molecular-level viscosity (0.02 cm-cm/s) and diffusivities (0.004 cm-cm/s) plus a numerically and physically motivated component based on the vertical cell Reynolds number

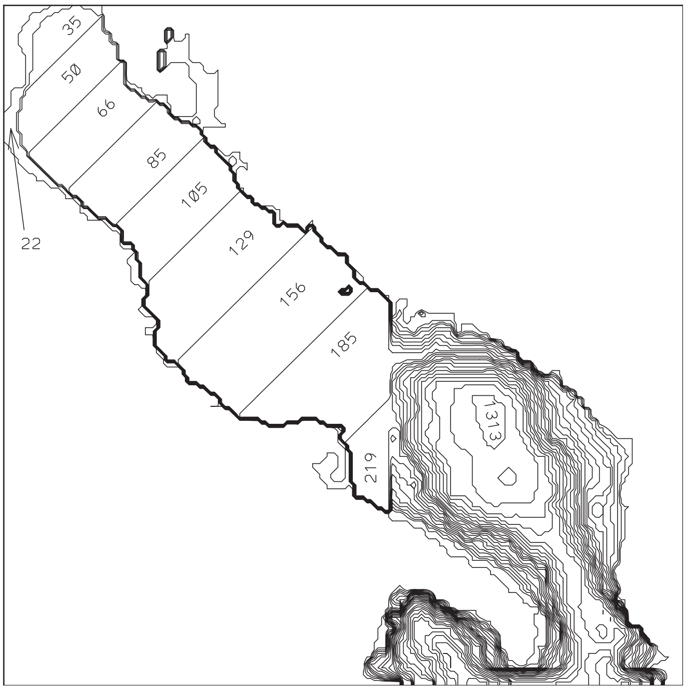

Fig. 8. – Contour plot of the smoothed bathymetry used to demonstrate the effect of removing the Mid Adriatic Pit. Step depths are given in meters for select steps.

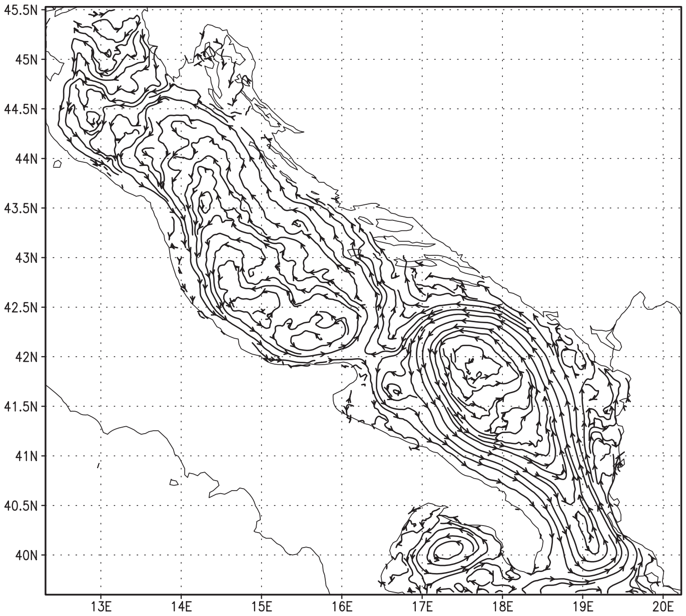

Fig. 9. – Streak line plot based on the mean field for the rerun of the fourth year but with the bathymetry shown in 8, that is without the Mid Adriatic Pit.

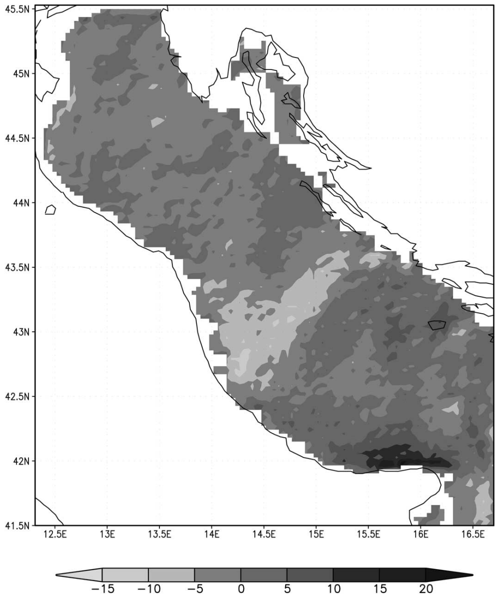

Fig. 10. – Component of the mean velocity in the northeast direction from the fourth year of the run with the bathymetry shown in fig. 2 (including the MAP).

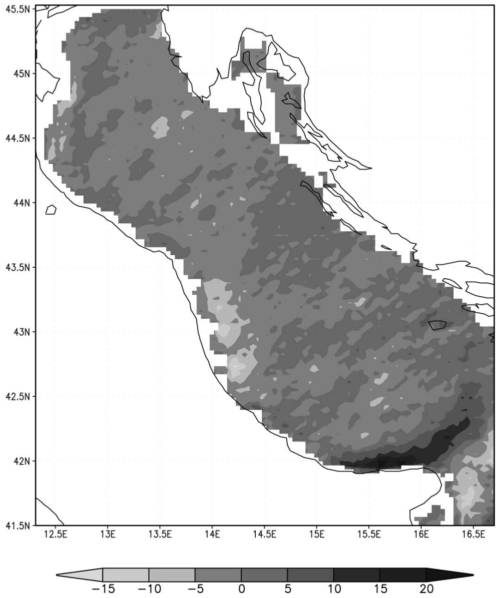

Fig. 11. – Component of the mean velocity in the northeast direction from the rerun of the fourth year with the bathymetry shown in fig. 8 (with no MAP).

and Richardson number. During the summer and in deeper layers, especially near the pycnocline, the mixing is near the laminar values. Lateral viscosity and diffusivities are specified constants (5 m-m/s), sufficiently small to allow realistic fronts and eddies, and wake recirculations downstream from major coastal abutments.

4. – Model performance

From a ten-year run of this Adriatic Sea implementation of DieCAST, we observed a number of features that verified the ability of the model to capture realistic features of the Adriatic Sea Dynamics. Among these are:

a) realistic triple gyre major general circulation features as shown in the streakline plot of fig. 3 (discussed further in the next section).

b) Realistic annual cycle surface T and S. The ten-year run showed convergence of the mean statistics to climatology. In fig. 4, we show the evolution of the horizontally averaged temperature and the annual cycle of this statistic taken from climatology. Notice that after just a few years the model mean temperature tracks the climatology very well save for some small interannual variation due to expected continuing temperature fluctuations.

c) Cross-Adriatic southwestward current over the northern flank of the Mid Adriatic Pit (discussed further in the next section).

d) Detailed fronts and eddies especially strong during the winter, with wintertime relative

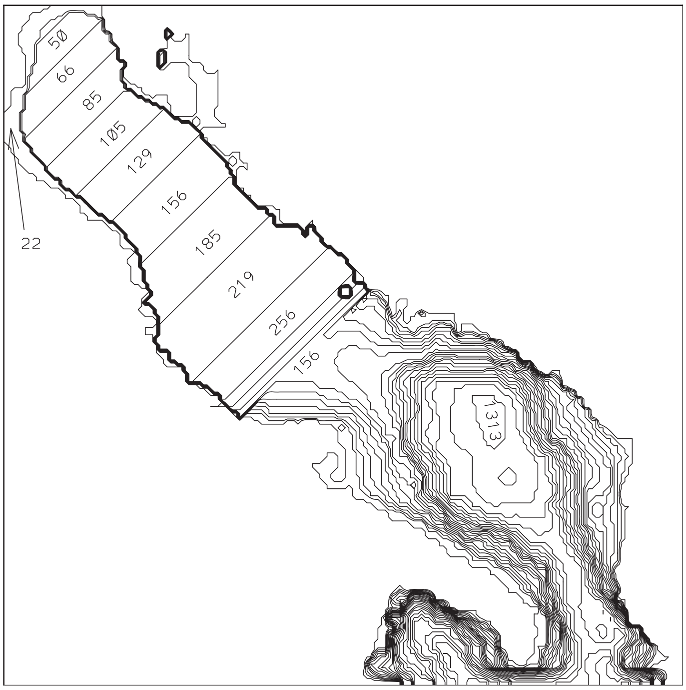

Fig. 12. – Contour plot of the bathymetry used to demonstrate the effect of a steep gradient in in the opposite sense of that on the northern flank of the the Mid Adriatic Pit. Step depths are given in meters for select steps.

vorticity locally exceeding the Earth's vertical rotation component; these intense eddies are energized by vigorous resolved slantwise convection that occurs due to weak or negative stratification during the winter.

e) Recirculation in the wake of the major Gargano Peninsula, especially during winter when reduced stratification allows finer-scale features to develop (fig. 5 shows a recirculation eddy in the lee of the Gargano Peninsula at the end of February in year 10); such recirculations require a highly inertial model to be addressed realistically; frontal eddies associated with the dominant southern gyre (see fig. 5) also interact with the flow near the Gargano.

f) The eastward mixing of the Po River plume during the late winter leading to a well-offshore southward transport associated with the laterally mixed buoyant region (see contour plots of salinity for the beginning of January and the end of March in fig. 6 and 7), similar to the Danube River dynamics in the Black Sea adaptation of DieCAST [4]; during the stable summer stratification periods, the plume is much closer to shore.

5. – Influence of the Mid Adriatic Pit

We first demonstrate that current flowing southwestward along the steep gradient on the northern flank of the MAP is reproduced by our simulation of the Adriatic. In these runs, we used a 2.5 min resolution. This spreads the "step" out to some extent, as shown in fig. 2, where we display the actual levels used in the computation; however, given the

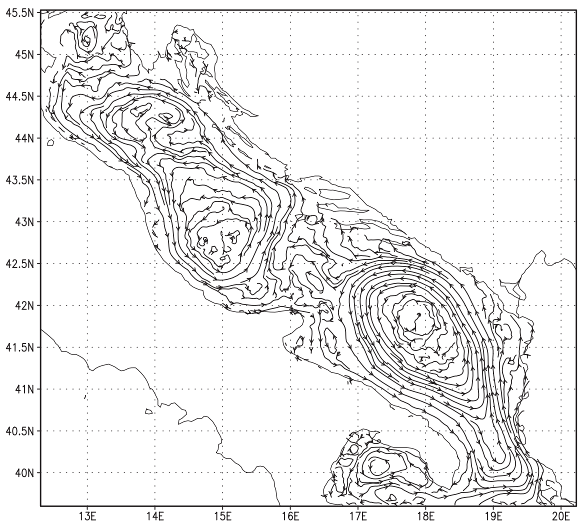

Fig. 13. – Streak line plot based on the mean field for the rerun of the fourth year but with the bathymetry shown in fig. 12. The steep slope in the mid Adriatic is now oriented in such a way as to produce a concentrated northeastward current and such a current results.

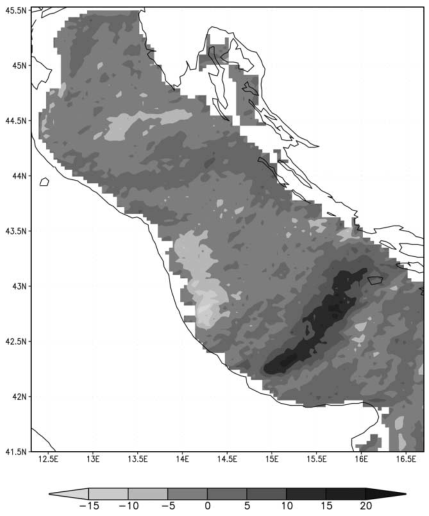

Fig. 14. – Mean velocity in the northeast direction from the rerun of the fourth year with the bathymetry shown in fig. 12 (with no MAP).

small diffusivity associated with the DieCAST model, this resolution proved adequate for our purposes.

We made an average of the velocity field over the 4th year of our simulation. This mean velocity field was then used to make streaklines to give an indication of the mean current directions. This mean streakline pattern is shown in fig. 3. Notice first of all the "three-gyre" cyclonic pattern of the mean current. As mentioned above, there is the rather robust cyclonic gyre over the SAP. Further north there is a cyclonic gyre with its northern side following the northern flank of the MAP in the anticipated direction. This is shown very clearly in fig. 10, where we plot the component of velocity in the northwest direction. Finally, there is the weaker northern cyclonic circulation extending almost to the northernmost reaches of the shallow end of the Adriatic. Instantaneous figures often show the northern flank MAP current, but sometimes this is obscured by the eddy field. This current appears to be the strongest and best organized in May and June and weakest in the winter.

In order to emphasize the importance of the bathymetry in establishing the current on the northern flank of the MAP, we performed another simulation for the same year four with everything exactly the same except for the bottom bathymetry. In this run we eliminated the MAP and replaced the "real" bathymetry with a smooth slope from the northern rim of the SAP to the northern end of the Adriatic. This bathymetry is shown in fig. 8. With this bathymetry, averaging the flow over the year results in the streakline plot shown in fig. 9. Now the circulation has only two large cyclonic gyres instead of the original three. The northern gyre now covers the area originally occupied by the MAP gyre and the northernmost gyre. This result establishes the importance of the

MAP in determining the 3-gyre circulation of the Adriatic. Comparing the plot of the northeastern component of velocity in fig. 10 with that in fig. 11 shows the importance of the steep topographic gradient in producing the MAF. Without that gradient, the MAF would not exist.

If there were a steep step crossing the Adriatic with a gradient opposite that of the northern flank of the MAP, then, according to the theory of Carnevale *et al.* [8], that should induce an intense current along the topographic contours in the opposite direction of that seen in fig. 10. To demonstrate this, we created another model bathymetry with such a "reverse" step-like bathymetry. This is shown in fig. 12. Here, the drop-off on the southern flank of the MAP has been made very steep, while the northern flank has been completely smoothed over. The mean circulation for a year-long flow over this bathymetry is shown in fig. 13 as a streakline plot. Here we see that although the SAP gyre is relatively unaffected, the two northern gyres have practically merged into one and the southern edge of this combined gyre is now sharply defined by an intense *northeastward* flow along the steep gradient of the southern flank of the MAP. Finally, in fig. 14, we again show the mean velocity component in the northeast direction. This is the counterpart to fig. 10. There is a nice contrast between the two cases showing the direction of the induced narrow cross-Adriatic currents depends on the sign of the topographic gradient.

6. – Conclusions

We created a 2.5 min resolution model of the Adriatic based on the DieCAST code. A simulation representing ten years of evolution was performed. The behavior of the model was found to be optimal. The general circulation pattern was correctly produced and the overall temperature and heat balances maintained over the period of evolution. Furthermore, the surface distribution temperature was found to be in accord with typical observations. In addition, the low viscosity of the model allowed the representation of realistic eddies generated by the flow passed the Gargano peninsula as well as the frontal eddies generated by the South Adriatic Pit current.

Given the overall success of the model, we turned to the question of the effect of the topographic feature known as the Mid Adriatic Pit on the Adriatic circulation. Observations had shown a distinct southwestward flow along the northern flank of this pit giving rise to the Mid Adriatic Filament. The topographic slope on northern flank is considerably steeper than that of the southern flank suggesting that the current is topographically generated. We demonstrated that our 2.5 min resolution model was capable of reproducing this current. We showed that if the steep slope were smoothed over, the coherent, relatively intense, narrow current would be replaced by a broad weak current. In addition, we demonstrated that the direction of the current is determined by the sign of the topographic gradient (and the direction of the rotation of the Earth) by running a simulation with a deformed topography containing a topographic step with opposite signed slope, and in that case the resulting current flowed in the opposite direction, that is to the northeast. These results were predicted by our barotropic quasi-geostrophic theory [8] for the much simpler system of a coastal current interacting with an escarpment. A detailed quantitative comparison with theory would require also capturing the effects of stratification as discussed elsewhere [1].

A recent study [31] has shown that flow in the MAP could provide a mean indicator of the characteristics of Northern Adriatic Deep Water as it varies seasonally and interannually. Given the influence of Northern Adriatic Deep Water in the Eastern Mediterranean, knowledge of what is going on in the MAP may also provide a precursor to conditions in the Eastern Mediterranean. This suggests that further detailed numerical study of flow in the MAP may prove valuable.

* * *

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